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RESEARCH MEMORANDUM

USE OF CHOKED NOZZLE TECHNIQUE AND EXHAUST JET DIFFUSER FOR EXTENDING OPERABLE RANGE OF JET-ENGINE RESEARCH FACILITIES

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation has been conducted to determine the increase in the useful ranges of flight conditions that may be obtained with a given jet-engine research facility when the choked nozzle technique or the exhaust jet diffuser, or both, are employed. This report describes these two methods, presents the considerations involved in their application, and gives typical results of their use as well as confirmation of the accuracy of data obtained by utilization of these techniques.

The validity and accuracy of the choked nozzle technique and the associated area - pressure-differential thrust correction term were substantiated by turbojet-engine and exhaust-nozzle performance data covering a range of nozzle pressure ratios up to about 10. It was demonstrated by calculations for a typical turbojet engine installed in a typical altitude test facility that a considerable increase in the range of flight conditions that can be investigated may be obtained by use of the choked-nozzle technique. It was also demonstrated that the range of facility exhaust pressures or exhauster flows may be increased by use of the exhaust-jet diffuser.

INTRODUCTION

High-altitude research facilities used for the investigation of jet engines at simulated flight conditions have certain limitations which, when coupled with the air-flow requirements of a given engine, govern the range of altitudes and flight Mach numbers that can be simulated. Frequently, the limitation is imposed by the inability of the exhaust system to handle the desired weight flow at the required vacuum or, conversely, to supply the desired vacuum at the required weight flow, with the result that it becomes impossible to simulate a desired range of flight conditions. Means of increasing the operational range of a facility exhaust system, and thus of the facility itself, are therefore desirable.

Two methods that have been employed both singly and in combination at the NACA Lewis laboratory to extend the useful range of facility regardless

exhaust systems are the utilization of engine exhaust-nozzle pressure ratios just sufficient to maintain choked flow (designated as the choked nozzle technique) irregardless of the flight conditions being simulated and the utilization of exhaust jet diffusers.

This report describes these methods, presents the considerations involved in their application, and gives typical results of their use, including a confirmation of the accuracy of data obtained by utilization of these techniques. Data obtained from a turbojet engine installed in the Lewis altitude wind tunnel and also from a conical exhaust nozzle installed in a bench setup are presented to confirm the accuracy of the choked-nozzle technique. Typical jet-diffuser performance curves obtained with exhaust jet diffusers installed on a turbojet-engine static sea-level test stand (reference 1) and on ram-jet-engine altitude-test-chamber installations are presented.

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CHOKED NOZZLE TECHNIQUE

The choked nozzle technique is a method of simulating high-altitude operating conditions with exhaust pressures higher than the simulated altitude ambient pressure. This technique may be applied to both ram-jet and turbojet engines with either incompletely expanded convergent or underexpanded convergent-divergent exhaust nozzles; for jet-engine research installations, however, its most convenient application is with respect to convergent nozzles. For this application the technique consists of increasing the engine exhaust pressure above the true altitude ambient pressure until the highest value at which sonic velocity may be maintained in the exhaust-nozzle throat is reached. (In order to assure the existence of sonic velocity, a nozzle pressure ratio of 1.9 to 2.0 is usually used.) It is evident that the technique can be used only with engines that would have exhaust-nozzle pressure ratios at the simulated flight condition greater than that required for sonic velocity in the nozzle throat if exhaust pressures corresponding to the operating altitudes were simulated. This condition of nozzle pressure ratio will be met to a greater or lesser degree by all present-day high-speed ram-jet and turbojet engines operating at their normal flight conditions.

As a result of this procedure, the pressure at the inlet to the exhauster equipment will be considerably higher than that which would be required for simulation of the operating altitude, and thus the exhausters will be able to handle a greater weight flow. The engine-inlet conditions will, of course, be unchanged and will correspond to those for the desired simulated flight condition. The engine internal flow conditions will be the same as those that would be obtained if the exact exhaust pressure altitude were simulated inasmuch as pressure changes downstream of the nozzle throat cannot be transmitted upstream because of the existence of sonic velocity in the nozzle throat.

The difference between the measured thrust and that which would be obtained when the exact exhaust pressure altitude is simulated may be simply determined from a consideration of the jet thrust equation applicable to an exhaust nozzle:

$$F_{j,a} = mV_{j,a} + A_n(p_n - p_{ex}) \tag{1}$$

where

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$mV_{j,a}$	velocity thrust term
$A_n(p_n - p_{ex})$	pressure thrust term
$V_{j,a} =$	$C_v \, V_{j,t}$

and the remaining symbols are defined in the appendix.

For the case of an engine equipped with a convergent exhaust nozzle that has a constant value of velocity coefficient (for nozzle pressure ratios greater than critical), the velocity thrust term will remain constant with changes in exhaust pressure. The difference between the actual measured thrust obtained with the choked nozzle technique and that which would be obtained with exact exhaust pressure altitude simulation will then be equal to the difference in pressure-thrust terms. Inasmuch as p_n will have the same value in both cases, this thrust difference reduces to

$$\Delta F_j = A_n \, \Delta p_{ex} \tag{2}$$

where Δp_{ex} is equal to the difference between the actual exhaust pressure and that required for exact altitude simulation. Thus, in those installations where the engine thrust is measured directly (on an engine thrust stand), a knowledge of the value of the velocity coefficient is not necessary (provided that it is constant) and the necessary thrust correction can be made by means of equation (2).

In other installations the thrust may be computed from pressure-rake measurements obtained at some point within the exhaust nozzle. For this case, a knowledge of the value of the velocity coefficient at the corrected condition as well as at the operating condition is essential if the flight thrust is to be determined. When a nozzle with a nonconstant velocity coefficient (for example, variable-area nonplanar-discharge clamshell nozzle) is used, then a knowledge of the values of the velocity coefficient is necessary regardless of the method of thrust determination. For the case of a jet engine designed for use with a convergent-divergent exhaust nozzle but investigated with a simple convergent nozzle installed, a complete knowledge of the velocity coefficients of both nozzles is essential before the experimentally determined thrust can be converted to flight thrust.

Some convergent exhaust nozzles that have been found to have a constant velocity coefficient are the simple conical-type nozzle and the variable-area clamshell-type nozzle having a planar discharge. Constant values of velocity coefficient ranging from about 0.95 to 0.99 have been reported by various investigators for both types of nozzle (for example, reference 2).

EXHAUST JET DIFFUSER

The exhaust jet diffusers investigated (fig. 1) function as sudden-expansion diffusers which utilize the kinetic energy of the engine exhaust jet to reduce the pressure downstream of the exhaust nozzle to a value below that supplied by the exhausters. (Further reduction in pressure just downstream of the exhaust nozzle could be obtained by the addition of a long conical subsonic diffuser (reference 1) to the downstream end of the shroud (fig. 1), but this would result in considerable installation complication in an altitude test facility and thus was not used.) Thus, with an exhaust jet diffuser installed on an engine, the exhausters will be able to handle a greater weight flow, inasmuch as they will be operating at a higher pressure. The use of this device will have no effect on engine performance at the simulated flight conditions provided the diffuser shroud or inlet pressure (p_5 in fig. 1) is measured and considered as the exhaust altitude pressure. Thus, it is possible to operate over an increased range of flight conditions without introducing a thrust correction factor. If, however, the jet diffuser is incapable of providing the desired range of flight conditions, greater range may be obtained by using it in combination with the choked nozzle technique, as will be discussed in a subsequent paragraph.

APPARATUS AND PROCEDURE

The validity and accuracy of the choked-nozzle technique was substantiated by data obtained during operation of an axial-flow turbojet engine which was installed in the Lewis altitude wind tunnel. The engine was equipped with a variable-area, planar-discharge clamshell-type exhaust nozzle which was held in a fixed position for this investigation. Air was supplied to the engine from the tunnel make-up air system through a duct that was connected to the engine inlet. A labyrinth-type slip joint prevented the transmission of forces from the engine inlet duct to the engine and thus permitted measurement of engine thrust by means of the tunnel balance system.

The procedure employed for obtaining the choked-nozzle turbojet-engine performance data was to vary the exhaust pressure from 628 to 894 pounds per square foot (exhaust altitudes from 30,000 to 22,000 ft) while the exhaust nozzle was choked and while the fixed conditions of

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engine inlet pressure and temperature, engine speed, and exhaust-nozzle area were maintained. The net thrust data obtained at the various exhaust pressure altitudes were corrected to a pressure altitude of 30,000 feet by means of the $A\Delta p$ term (equation (2)) previously described; the air and fuel-flow data, on the other hand, are those corresponding to the simulated operating condition of 0.78 Mach number and 30,000 feet altitude and thus require no correction for the change in exhaust pressure altitude. These values were then compared with those obtained at the simulated exhaust altitude of 30,000 feet.

Further demonstration of the validity of the choked nozzle technique was obtained by the application of the $A\Delta p$ correction term to thrust data obtained during the operation of a conical nozzle in a bench setup. This setup is actually a miniature altitude test chamber and employs a system of thrust measurement similar to that used in the full-scale Lewis altitude test chambers. This system includes a labyrinth-type seal installed at the inlet of the nozzle to isolate it from the inlet-air ducting and a bell-crank mechanism which transmits the nozzle forces to an air-balanced diaphragm. The nozzle was of the simple conical type with a half angle of 16°, an exit to inlet area ratio of 0.5, and an exit area of 86.7 square inches.

The pressure ratio across the nozzle was varied from slightly over 1.0 to approximately 10.0 by varying both the inlet and exhaust pressures. (The air flow accompanying the changes in pressure ranged from 15 to 83 lb/sec.) In order to generalize the nozzle data and eliminate the effect of the variation of inlet pressure, the nozzle jet thrust was corrected by dividing by δ, which is defined as the ratio of nozzle-inlet total pressure to NACA standard sea-level pressure $(\delta = P_4/2116)$. The calculated jet thrusts for nozzle pressure ratios greater than critical were determined by adding the calculated $A\Delta p$ term (equation (2)) for the particular operating exhaust pressure to the measured thrust obtained at critical pressure ratio. A comparison was then made between the measured and calculated values of jet thrust.

The performance curves for the exhaust jet diffusers were determined from data presented in reference 1 and also from unpublished data obtained on several full-scale altitude tank installations. For the tests of reference 1, the fluid medium was engine exhaust gas ranging in temperature from about 1200° to 1600° R and for the unpublished jet diffuser tests, the fluid was exhaust gas ranging in temperature from 3000° to 3900° R.

DISCUSSION OF RESULTS

Choked Nozzle Technique

The effect of varying exhaust pressure from 628 to 894 pounds per square foot (exhaust altitudes from 30,000 to 22,000 ft) on the performance of an axial-flow turbojet engine operating with a choked exhaust nozzle and with inlet conditions constant at a simulated altitude of 30,000 feet is presented in figure 2. The thrust data for the various exhaust pressures were corrected to a pressure altitude of 30,000 feet by means of the $A\Delta p$ term previously mentioned. It is evident that when the exhaust nozzle is choked, the following three variables: (1) specific fuel consumption, (2) net thrust, and (3) air flow are unaffected, within the normal scatter of the data, by these increases in exhaust pressure.

The increase in exhauster flow corresponding to the over-all increase in exhaust pressure (628 to 894 lb/sq ft abs.) would amount to about 40 percent. Thus, as long as the exhaust nozzle is choked, increases in exhaust pressure will permit considerable increases in exhauster flow without affecting engine performance. Therefore, the choked nozzle technique would permit testing of engines of larger size relative to the facility mass-flow limitations, or would permit testing a given engine over a wider range of simulated altitude or flight speed conditions. Although the data presented were limited to a narrow range of simulated altitudes by the particular facility limitations, it is expected that the same agreement would be obtained over much wider ranges regardless of the facility.

The variation of corrected jet thrust with nozzle pressure ratio for pressure ratios up to about 10 for the 16° half-angle conical nozzle installed in the bench setup is presented in figure 3. The circle data points represent experimentally determined thrust values obtained from the thrust measuring system and the squares represent thrust values computed by adding the previously mentioned $A\Delta p$ term (equation (2)) to the measured thrust obtained at critical pressure ratio. Excellent agreement is seen to exist between both the measured and computed values of corrected thrust over the entire range investigated; the validity of the $A\Delta p$ term is thus substantiated.

The increase in operable facility range that may be obtained by use of the choked nozzle technique is illustrated in figure 4 which presents envelopes of the flight conditions obtainable when a typical turbojet engine is installed in a typical jet-engine test facility. (The exhausters for this facility are essentially constant-volume machines.)

The upper altitude limit of the choked-exhaust-nozzle envelope is imposed by the minimum pressure that the exhausters would be able to

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supply and the lower altitude limit is imposed by the maximum flow the exhausters would be able to handle. Both the upper and lower altitude limits of the simulated exhaust altitude envelope are determined by the performance of the exhausters in conjunction with the engine air-flow requirements. The decrease in maximum operable altitude with an increase in flight Mach number (upper half of curve) that exists for the simulated exhaust altitude envelope is a result of the fact that the increased engine air-flow requirement cannot be pumped by the exhausters except at an increased pressure. The increase in minimum operable altitude with an increase in Mach number (lower half of limit curve) is a result of the nearly constant exhauster mass flow in the region of high exhaust pressures or low altitudes, so that operation at the higher flight Mach numbers is possible only at higher altitudes.

It is obvious that a considerably greater range of altitudes and flight Mach numbers may be investigated by use of the choked nozzle technique as compared with that obtainable by means of exhaust altitude simulation. Thus, for the particular engine-facility combination discussed, use of the choked nozzle technique permits operation over a band of altitudes 50,000 feet wide extending from a minimum altitude of 20,000 feet at zero Mach number to a minimum altitude of 64,000 feet at a Mach number of 3.0. When the simulated exhaust altitude technique is used, the altitude range of operation extends from 20,000 to 50,000 feet at zero Mach number and narrows as flight Mach number is increased until at a Mach number of 0.45 operation is possible only at an altitude of 35,000 feet. Similar gains could be obtained for other engines installed in other facilities; the exact amount of the gain, in each case, would depend upon the characteristics and relative air-handling capacities of the particular engine and facility.

Exhaust Jet Diffuser

The variation of exhaust-jet-diffuser pressure ratio p_7/p_5 (see fig. 1) with exhaust-nozzle pressure ratio is presented in figure 5 for diffuser area ratios A_5/A_7 of 0.86, 0.56, and 0.41. A theoretical curve for an area ratio of 0.86 is also included for comparison. This curve was determined from the following equation:

$$\left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = 1 + \frac{\frac{\gamma-1}{2} + \frac{p_7}{p_5} - \frac{\gamma+1}{2}\left(\frac{p_7}{p_5}\right)^2}{\frac{2\gamma}{\gamma-1}\left(\frac{A_5}{A_7}\right)\left[\gamma\left(\frac{A_5}{A_7} - 1\right) + 1 - \frac{p_7}{p_5}\right]} \tag{3}$$

which is based on the gas law and the laws of conservation of energy, momentum, and mass flow. It was assumed in the derivation of this equation that the increase in the area of the exhaust jet due to free expansion may be neglected (see reference 1).

It is to be noted that the diffuser pressure recovery (jet diffuser pressure ratio) increases as nozzle pressure ratio and diffuser area ratio are increased. A point of maximum pressure recovery defined as a choking limit (see reference 1) was encountered at nozzle pressure ratios of 3.2 and 4.3 for area ratios of 0.86 and 0.56, respectively. This maximum was not encountered with an area ratio of 0.41 for the range of nozzle pressure ratios covered. 2483

A comparison of the theoretical and experimental curves for an area ratio of 0.86 indicates reasonably good agreement at the lower pressure ratios with an increasing difference between the two curves as pressure ratio is increased. This difference is the result of friction and separation losses, and of the simplifying assumption that was used in deriving the equation of the theoretical curve. Inasmuch as the assumption is less applicable for the lower area ratios, poorer agreement between experimental and theoretical values would probably result if similar comparisons were made for the area ratios of 0.56 and 0.41.

A consideration of the jet diffuser characteristics as applied to a jet-engine research facility indicates that for best diffuser recovery, and thus maximum increase in exhauster flow, it is desirable to operate at as high an area ratio as possible without exceeding the choking limit. If operation at high nozzle pressure ratios is desired, then the diffuser area ratio must be reduced.

A replot of the curves of figure 5 is given in figure 6 which presents over-all pressure ratio P_4/p_7 as a function of nozzle pressure ratio. The most interesting aspect of these curves is that they indicate that the over-all pressure ratio and nozzle pressure increase and decrease together. Thus, if it is desired to operate a jet engine at a specified operating condition with the highest exhaust pressure and mass flow possible (lowest over-all pressure ratio), it is obvious that in addition to the highest possible jet-diffuser area ratio, the lowest possible nozzle pressure ratio must be used. In most cases, the exhaust nozzle would normally be choked and thus operation with the lowest exhaust-nozzle pressure ratio will generally require operation with the choked nozzle technique (hence, a nozzle pressure ratio of 1.9). For this case the addition of the exhaust jet diffuser of highest area ratio investigated (0.86) would result in an over-all pressure ratio of 1.49 instead of 1.9 so that the exhausters can thus operate at a pressure of approximately 1.27 times that which would be required without the jet diffuser (even with choked nozzle technique). It is thus evident that the limiting exhaust altitude pressure or flow of a given jet-engine research facility may be extended by the use of the exhaust jet diffuser and that the most benefit may be obtained from the jet diffuser when it is employed in conjunction with the choked nozzle technique.

The accuracy of jet-engine thrust data obtained with an exhaust jet diffuser installed has been verified in reference 1 (sea-level static-test-stand investigation), which presents a comparison of engine data obtained with and without the jet diffuser. These data indicate that the values of jet thrust, air flow, and fuel flow obtained with and without the jet diffuser installed agreed within about $1\frac{1}{2}$ percent, which is within the normal experimental accuracy of these data.

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SUMMARY OF RESULTS

An investigation was conducted to determine the practicability of using the choked nozzle technique and exhaust jet diffuser for extending the useful ranges of flight conditions that may be investigated with a given jet engine research facility. This investigation indicated that the validity and accuracy of the choked nozzle technique and the associated $A\Delta p$ thrust correction term have been substantiated by turbojet engine and nozzle performance data covering a range of nozzle pressure ratios up to about 10. It was demonstrated by calculations for a typical turbojet engine installed in a typical altitude test facility that a considerable increase in the range of flight conditions that can be investigated may be obtained by use of the choked nozzle technique. It was also demonstrated that an increase in the range of facility exhaust pressures or exhauster flows can be realized by the use of exhaust jet diffusers. The choked nozzle technique and jet diffuser may therefore be employed either singly or in combination to increase the operable range of a jet engine research facility without the introduction of error into the engine data.

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APPENDIX - SYMBOLS

A	area, sq ft
A_n	nozzle exit area, sq ft
C_v	nozzle velocity coefficient = V_a/V_t
D	diameter, ft
F_j	jet thrust, lb
L	ejector shroud length (see fig. 1), ft
m	mass flow, slugs/sec
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
p_n	static pressure in exhaust nozzle throat, lb/sq ft
V_j	exhaust jet velocity, ft/sec
γ	ratio of specific heats
δ	pressure correction factor = $P_4/2116$

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Subscripts (see fig. 1):

a	actual
t	theoretical
4	nozzle inlet
5	nozzle throat or exit
6	station where jet strikes shroud wall
7	shroud exit

REFERENCES

1. Essig, Robert H., Bohannon, H. R., and Gabriel, David S.: Jet Diffuser for Simulating Ram Pressure and Altitude Conditions on a Turbojet-Engine Static Test Stand. NACA TN 1687, 1947.

2. Grey, R. E., and Wilsted, H. D.: Performance of Conical Jet Nozzles in Terms of Flow and Velocity Coefficients. NACA Rep. 933, 1949. (Supersedes NACA TN 1757, 1948.)

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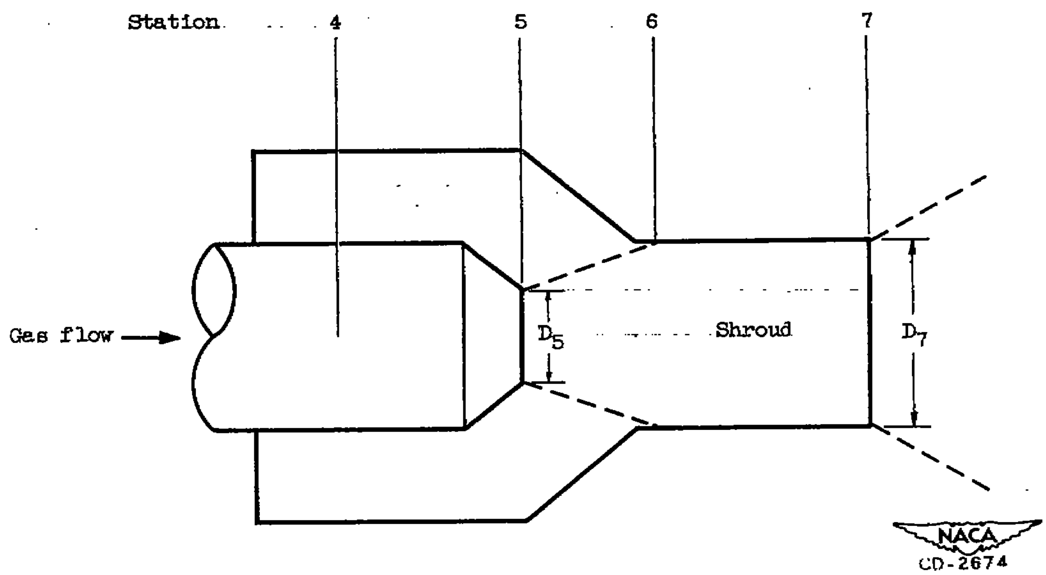

Figure 1. - Schematic diagram of exhaust jet diffuser.

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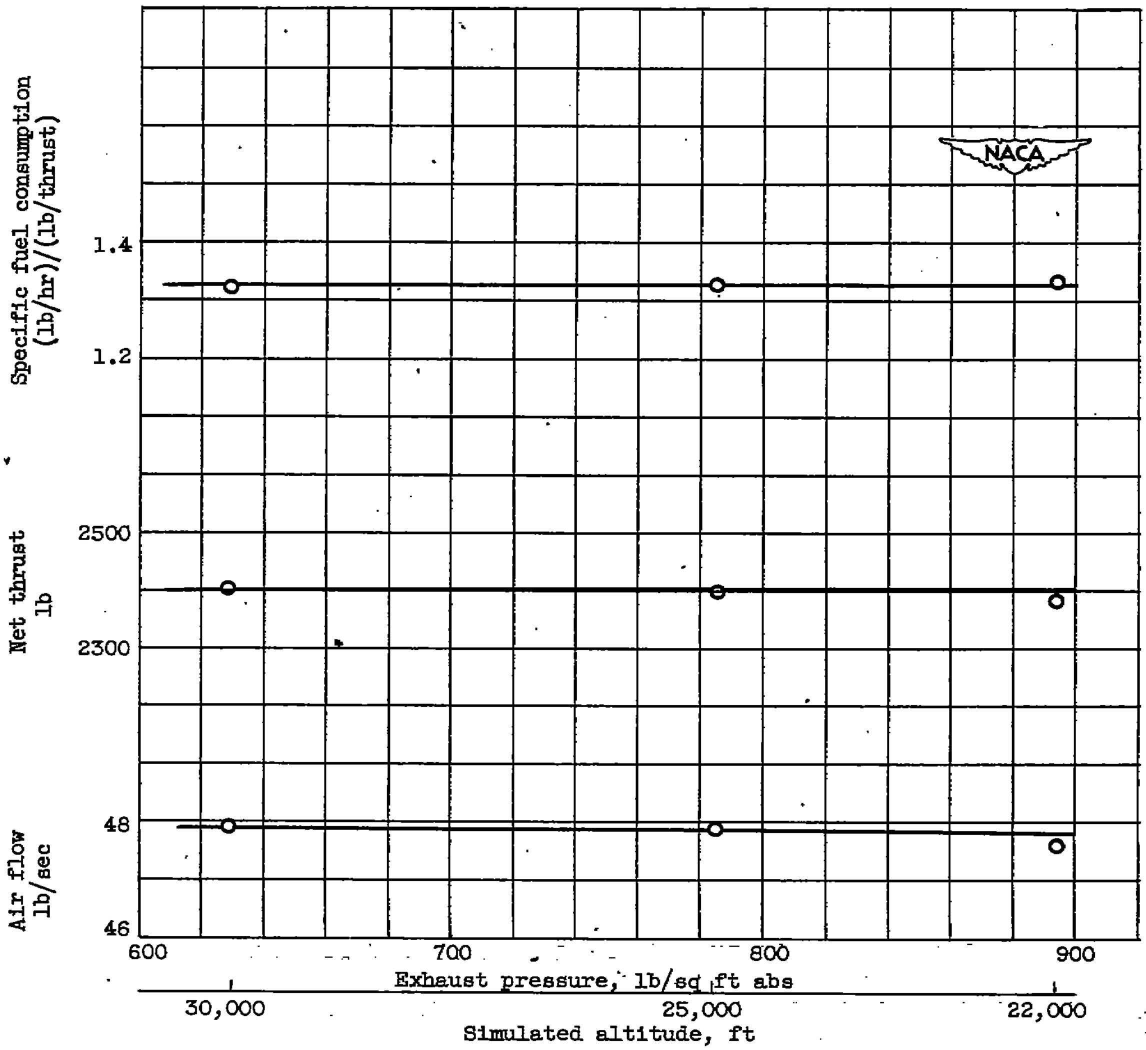

Figure 2. - Effect of varying exhaust pressure on performance of turbojet engine operating with choked exhaust nozzle. Simulated engine-inlet conditions: altitude, 30,000 feet; Mach number, 0.78.

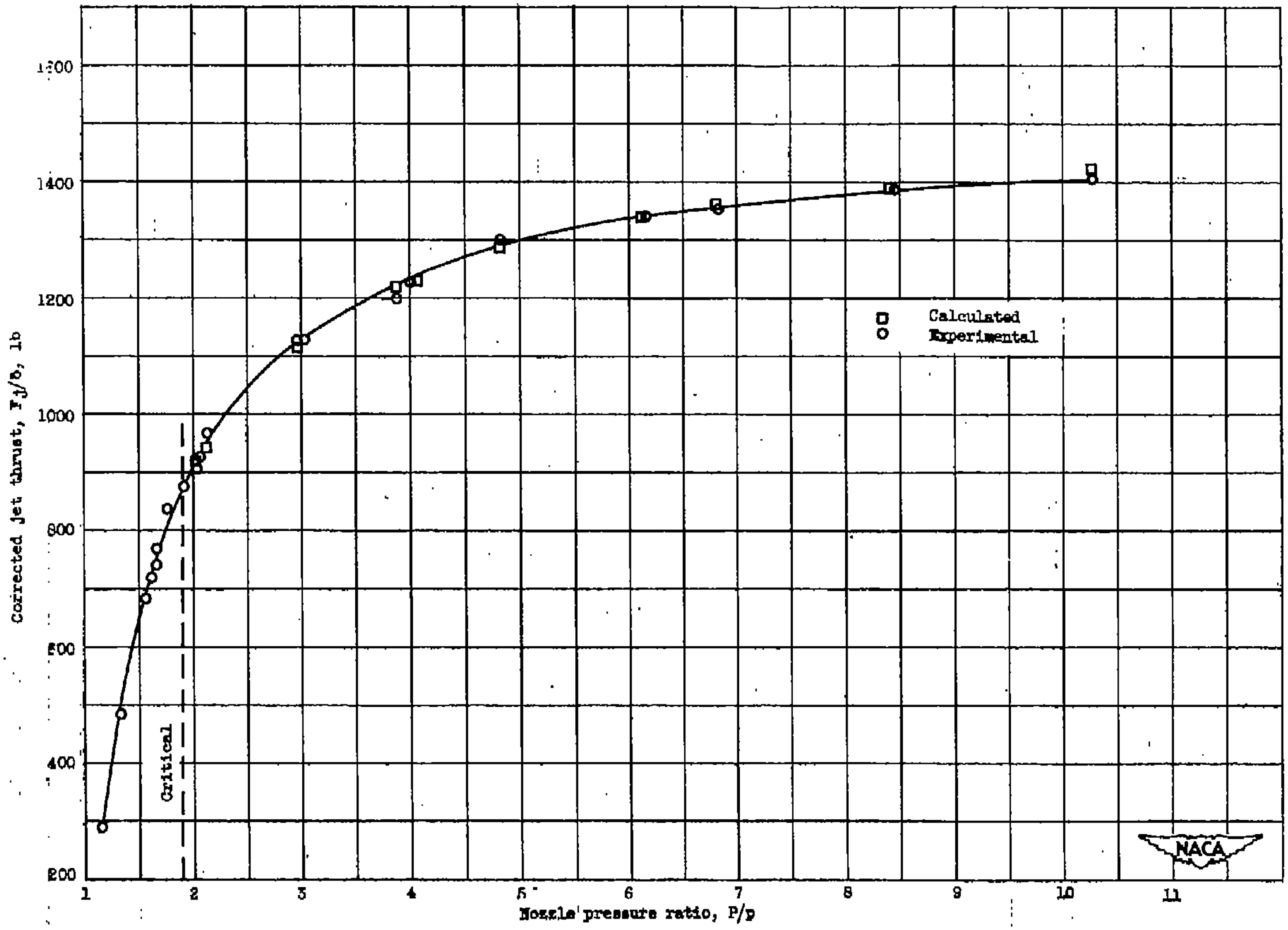

Figure 3. - Variation of corrected jet thrust with nozzle pressure ratio (upstream total to ambient) for conical nozzle. Inlet to exit area ratio, 2.0; exit area, 86.7 square inches; half angle, 16°; inlet-air temperature, 85° to 90° F.

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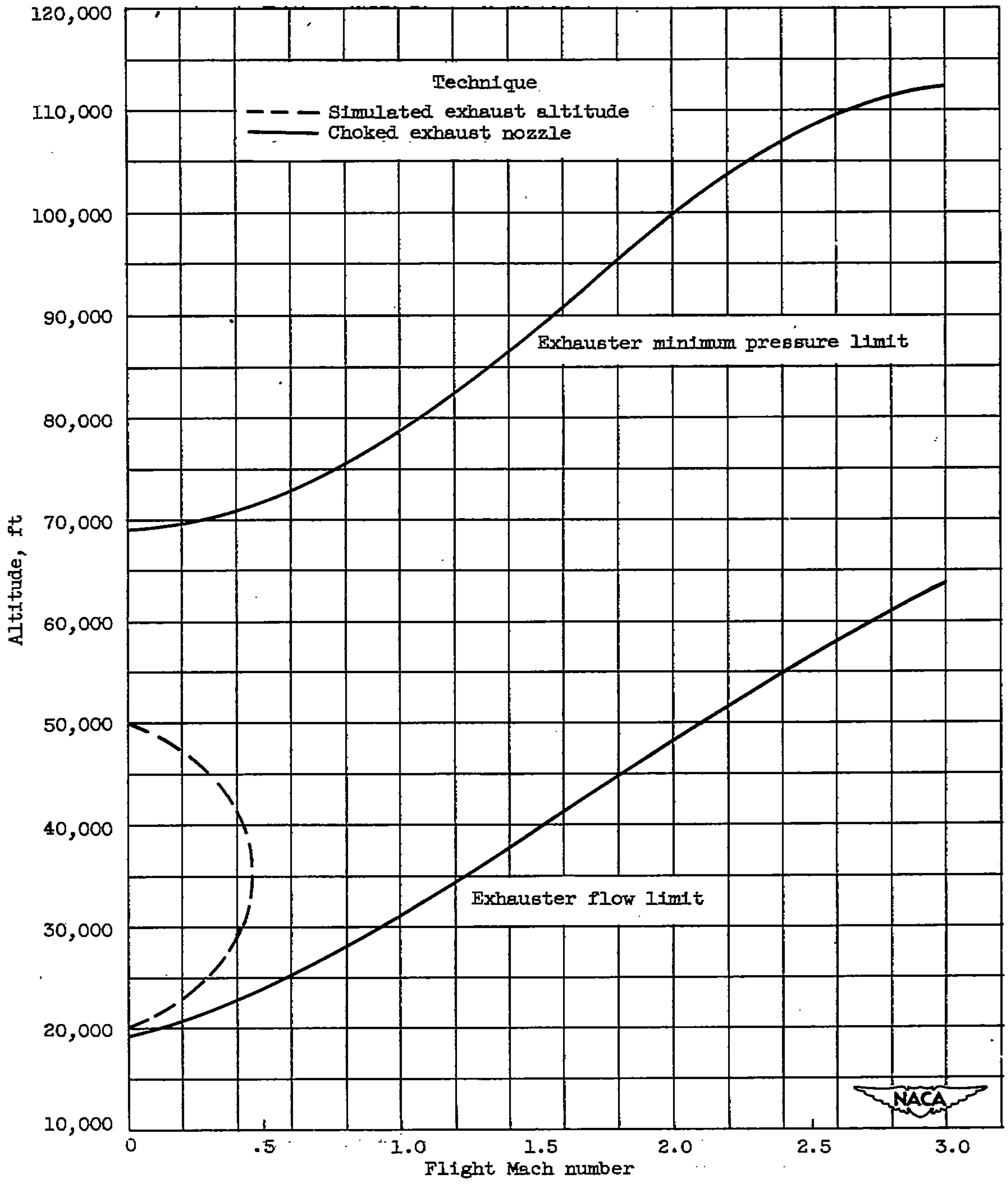

Figure 4. Comparison of effect of choked nozzle and simulated altitude techniques on operable range of typical jet-engine facility with typical jet engine installed.

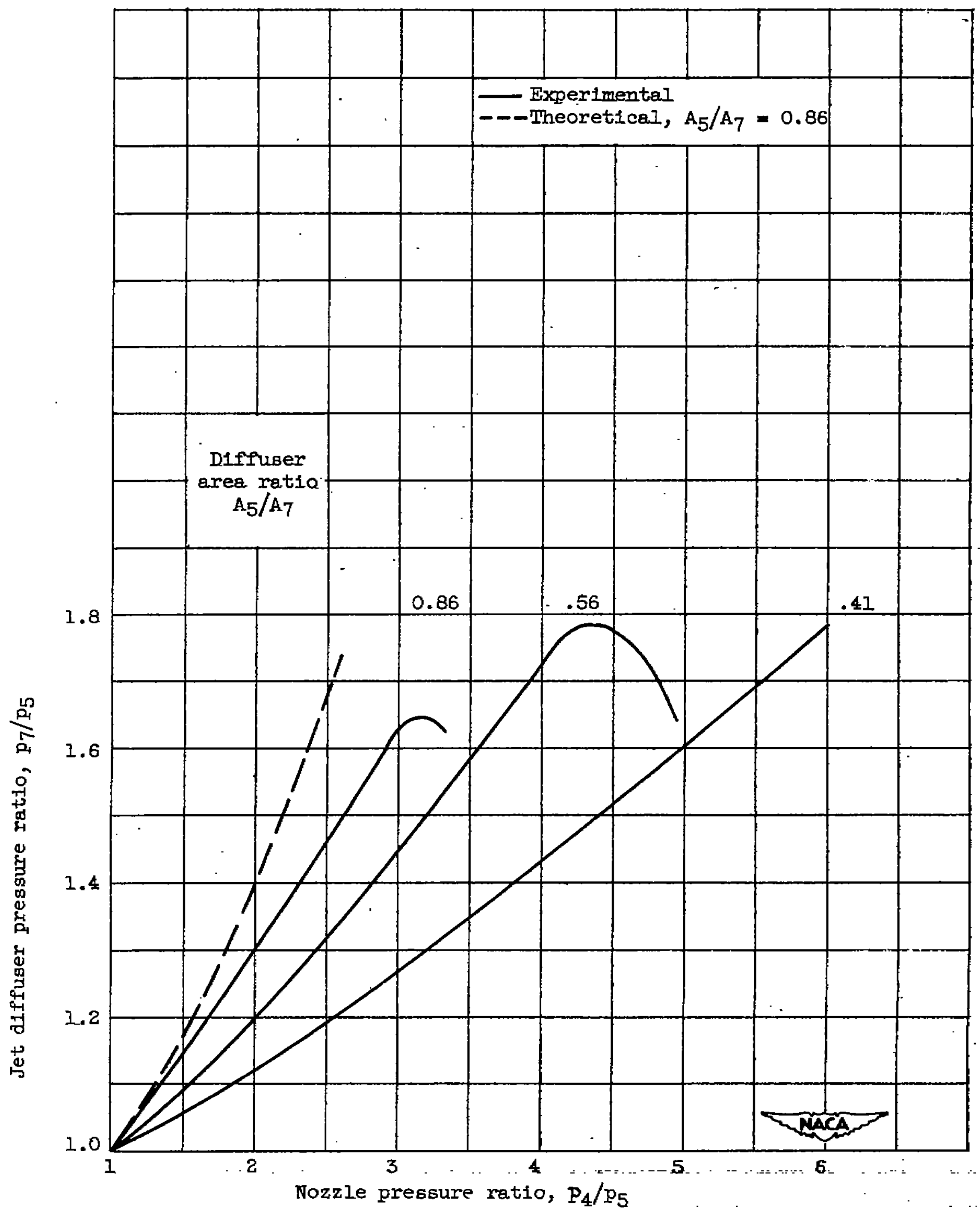

Figure 5. --Experimental variation of jet diffuser pressure ratio with exhaust-nozzle pressure ratio for several exhaust jet diffusers.

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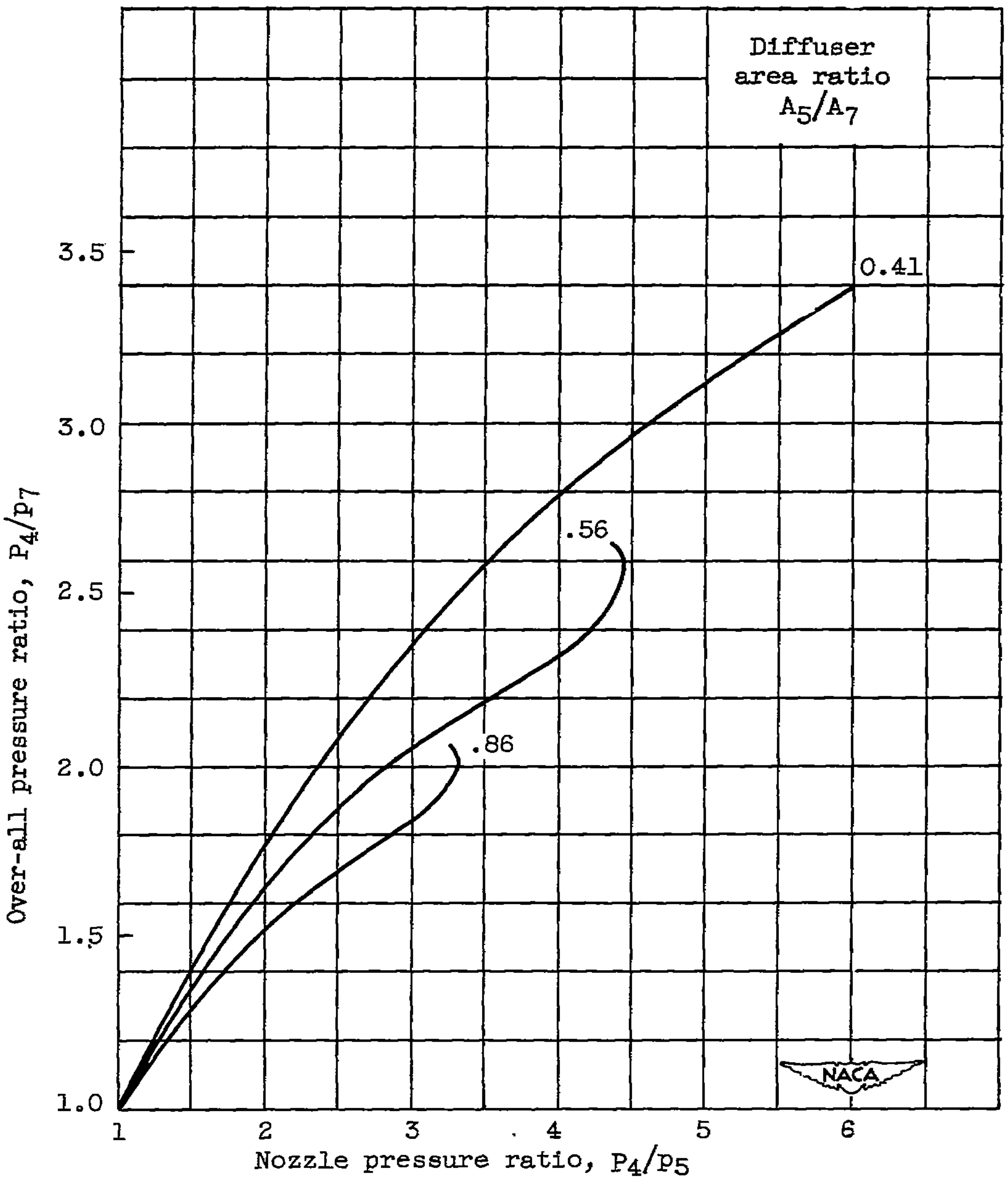

Figure 6. - Variation of over-all pressure ratio with nozzle pressure ratio for several exhaust jet diffusers.